Threaded Steel Fasteners

Revised by the ASM Committee on Threaded Steel Fasteners*

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Specification and Selection

Specifications are used to outline fastener requirements, to control the manufacturing process, and to establish functional or performance standards. Their goal is to ensure that fasteners will be interchangeable, dimensionally and functionally. The most common fastener specifications are product specifications that are set up to govern and define the quality and reliability of fasteners before they leave the manufacturer. These specifications determine what material to use; state the objectives for tensile strength, shear strength, and response to heat treatment; set requirements for environmental temperature or atmospheric exposure; and define methods for testing and evaluation. To ensure proper use of fasteners, additional specifications are necessary as a guide to proper design, application and installation. All American Society for Testing and Materials (ASTM) and Society of Automotive Engineers (SAE) specifications covering threaded fasteners require that the fastener be marked for grade identification (Table 1). Grade markings are a safety device that provide a positive check on selection, use, and inspection.

Table 1 Various ASTM and SAE grade markings for steel bolts and screws

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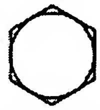
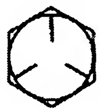
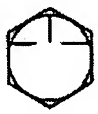
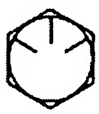
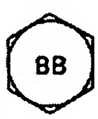
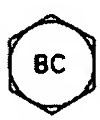
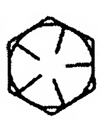
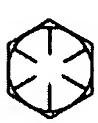
Grade marking	Specification	Material
 No mark	SAE grade 1	Low- or medium-carbon steel
	ASTM A 307	Low-carbon steel
	SAE grade 2	Low- or medium-carbon steel
	SAE grade 5 ASTM A 449	Medium-carbon steel, quenched and tempered
	SAE grade 5.1	Low- or medium-carbon steel, quenched and tempered
	SAE grade 5.2	Low-carbon martensite steel, quenched and tempered
	ASTM A 325, type 1	Medium-carbon steel, quenched and tempered
	ASTM A 325, type 2	Low-carbon martensite steel, quenched and tempered
	ASTM A 325, type 3	Atmospheric corrosion (weathering) steel, quenched and tempered
	ASTM A 354, grade BB	Low-alloy steel, quenched and tempered
	ASTM A 354, grade BC	Low-alloy steel, quenched and tempered
	SAE grade 7	Medium-carbon alloy steel, quenched and tempered. Roll threaded after heat treatment
	SAE grade 8	Medium-carbon alloy steel, quenched and tempered
	ASTM A 354,	Alloy steel,

The selection and satisfactory use of a particular fastener are dictated by the design requirements and conditions under which the fastener will be used. Consideration must be given to the purpose of the fastener, the type and thickness of materials to be joined, the configuration and total thickness of the joint to be fastened, the operating environment of the installed fastener, and the type of loading to which the fastener will be subjected in service. A careful analysis of these requirements is necessary before a satisfactory fastener can be selected. The selection of the correct fastener or fastener system may simply involve satisfying a requirement for strength (static or fatigue) or for corrosion resistance. On the other hand, selection may be dictated by a complex system of specification and qualification controls. The extent and complexity of the system needed is usually dictated by the probable cost of a fastener failure. Additional information is available in the article "Failures of Mechanical Fasteners" in *Failure Analysis and Prevention,* Volume 11 of *ASM Handbook.*

Adequate testing is the most practical method of guarding against the failure of a new fastener system for a critical application. The designer must not extrapolate existing data to a different size of the same fastener, because larger-diameter fasteners have significantly lower fatigue endurance limits than smaller-diameter fasteners made from the same material and using the same manufacturing techniques and joint system.

Strength Grades and Property Classes

Although chemical composition can be an important factor when specifying and selecting threaded fasteners for many applications (particularly when the applications require elevated-temperature service, corrosion resistance, or good hardenability characteristics with adequate toughness properties), the primary criterion in selecting threaded fasteners involves the specification of strength levels. Consequently, the grade or class of bolts, studs, and nuts are widely used to designate the various strength or performance level of threaded fasteners in the specifications developed by the Society of Automotive Engineers, the International Organization for Standardization (ISO), the American Society for Testing and Materials, and/or the Industrial Fasteners Institute (IFI). This allows the purchaser of steel bolts, studs, and nuts to select the desired strength level by specifying a grade or class in the SAE, ISO, ASTM, or IFI specifications. The producer then selects a particular steel grade that meets the broad chemical composition ranges allowed in these specifications. This enables the producers to use the most economical material consistent with their equipment and production procedures to meet the specified properties. As a result, producers have adopted substantially the same manufacturing process for a given class of product, which has resulted in a certain degree of steel grade standardization. The strength and property designations of bolts and studs are typically based on minimum tensile (breaking) strength, while the grade designations of nuts are typically based on proof stress.

The following two sections describe the commonly used ISO and SAE grade designations for steel threaded fasteners made in metric sizes or in the U.S. system of inch dimensions. Of course, other specifications (such as some of the ASTM specifications listed in Table 1) may use their own grade designation systems.

Property class designations of metric fasteners are defined in ISO R898 and SAE J1199. The commonly used property classes of steel bolts and nuts made in metric sizes are given in Tables 2 and 3, respectively. In Tables 2 and 3, the property class numbers indicate the general level of tensile strength for bolts or proof stress for nuts in megapascals. In Table 3, for example, ISO class 9 nuts have a proof stress ranging from 900 to 920 MPa. In Table 2, the number following the decimal point in a class number for a bolt or stud indicates the ratio of the yield strength to the tensile strength; for example, an ISO class 5.8 stud has a tensile strength of 520 MPa and a yield strength of 420 MPa.

Table 2 ISO property classes and SAE strength grades for steel bolts and studs (including cap screws and U-bolts)

The minimum reduction in area for specimens machined from all the grades and classes of fasteners listed is 35%.

Strength grade or property class	Nominal diameter	Proof stress[a]		Minimum tensile strength[b]		Minimum yield strength[c][d]		Minimum elongation,	Maximum surface hardness,	Core hardness,
		MPa	ksi	MPa	ksi	MPa	ksi	%[c]	HR30N	HRC
ISO property classes[e] for metric sizes										

4.6	5-100 mm	225	33	400	58	240[f]	35[f]	22	...	67-95 HRB
4.8	1.6-16 mm	310	45	420	61	340	49	14	...	71-95 HRB
5.8[g]	5-24 mm	380	55	520	75	420	61	10	...	82-95 HRB
8.8	16-72 mm	600	87	830	120	660	96	12	53[h]	23-34
9.8	1.6-16 mm	650	94	900	131	720	104	10	56[h]	27-36
10.9	5-100 mm	830	120	1040	151	940	136	9	59[h]	33-39
12.8[i]	1.6-20 mm	940	136	1220	177	976	142	...	62[h]	38-43
12.9[i]	1.6-36 mm	970	141	1220	177	1100	160	8	63[h]	39-44
SAE strength grades[j] for sizes in U.S. system of inch dimensions										
1	$\frac{1}{4}$-1$\frac{1}{2}$ in.	225	33	415	60	250[f]	36[f]	18	...	70-100 HRB
2	$\frac{1}{4}$-$\frac{3}{4}$ in.[k]	380	55	510	74	395	57	18	...	80-100 HRB
	>$\frac{3}{4}$-1$\frac{1}{2}$ in.	225	33	415	60	250[f]	36[f]	18	...	70-100 HRB
4[l]	$\frac{1}{4}$-1$\frac{1}{2}$ in.	450	65	795	115	690	100	10	...	22-32
5	$\frac{1}{4}$-1 in.	585	85	830	120	635	92	14	54	25-34
	>1-1$\frac{1}{2}$ in.	510	74	725	105	560	81	14	50	19-30
5.1[m]	$\frac{5}{8}$-$\frac{1}{2}$ in.	585	85	830	120	...	...	...	50	25-40
5.2[n]	$\frac{1}{4}$-1 in.	585	85	830	120	635	92	14	56	26-36
7[n][o]	$\frac{1}{4}$-1$\frac{1}{2}$ in.	725	105	915	133	795	115	12	54	28-34
8	$\frac{1}{4}$-1$\frac{1}{2}$ in.	830	120	1035	150	895	130	12	58.6	33-39
8.1[l]	$\frac{1}{4}$-1$\frac{1}{2}$ in.	830	120	1035	150	895	130	10	...	32-38
8.2[n]	$\frac{1}{4}$-1 in.	830	120	1035	150	895	130	10	58.6	33-39

(a) Determined on full-size fasteners.

(b) Determined on both full-size fasteners and specimens machined from fasteners.

(c) Determined on specimens machined from fasteners.

(d) Yield strength is stress to produce a permanent set of 0.2%.

(e) Data from ASTM F 568 or SAE J1199. Values are for fasteners with coarse threads.

(f) Yield point instead of yield strength for 0.2% offset.

(g) Class 5.8 requirements apply to bolts and screws with lengths 150 mm (6 in.) and shorter and to studs of all lengths.

(h) In SAE J1199, surface hardness shall not exceed base metal hardness by more than two points on the HRC scale or shall not exceed the maximums given.

(i) As of Sept 1983, class 12.8 and 12.9 bolts were removed from SAE J1199 because of environmentally assisted cracking of 12.8 bolts in automotive rear suspensions. Caution is advised when considering the use of class 12.8 or 12.9 bolts and screws. Capability of the bolt manufacturer, as well as the anticipated in-use environment, should be considered. High-strength products such as class 12.9 require rigid control of heat-treating operations and careful monitoring of as-quenched hardness, surface discontinuities, depth of partial decarburization, and freedom from carburization. Some environments may cause stress-corrosion cracking of nonplated as well as electroplated products.

(j) Data from SAE J429.

(k) For bolts and screws longer than 150 mm (6 in.), grade 1 requirements apply.

(l) Studs only.

(m) No. 6 screw and washer assemblies (sems) only.

(n) Bolts and screws only.

(o) Roll threaded after heat treatment

Table 3 ISO property classes and SAE strength grades for steel nuts

The following classes or grades do not normally include jam, slotted, castle, heavy, or thick nuts.

Strength grade or property class	Nominal diameter	Proof stress[a]		Rockwell hardness, HRC	
		MPa	ksi	Minimum	Maximum
ISO property classes[b]					
5[c]	1.6-2.5 mm	520	75	70 HRB	30
	3-4 mm	520	75	70 HRB	30
	5-6 mm	580	84	70 HRB	30
	8-10 mm	590	86	70 HRB	30
	12-16 mm	610	89	70 HRB	30
	20-36 mm	630	91	78 HRB	30
	42-100 mm	630	91	70 HRB	30
9[c]	3-4 mm	900	130	85 HRB	30
	5-6 mm	915	133	89 HRB	30
	8-10 mm	940	136	89 HRB	30
	12-16 mm	950	138	89 HRB	30
	20-36 mm	920	133	89 HRB	30
	42-100 mm	920	133	89 HRB	30
10[c]	1.6-10 mm	1040	151	26	36
	12-16 mm	1050	152	26	36
	20-36 mm	1060	154	26	36
12[c]	3-6 mm	1150	167	26	36
	8-10 mm	1160	168	26	36
	12-16 mm	1190	173	26	36
	20-36 mm	1200	174	26	36
	42-100 mm	1200	174	26	36
85 and 853[c][d]	12-36 mm	1075	156	89 HRB	38
105 and 1053[c][d]	12-36 mm	1245	181	26	38
SAE strength grades[e] for nuts in U.S. system of inch sizes					
2[f]	$\frac{1}{4}$-1$\frac{1}{2}$ in.	620	90	...	32
5	$\frac{1}{4}$-1 in.	830	120[g]	...	32
		750	109[h]	...	32
	>1-1$\frac{1}{2}$ in.	725	105[e]	...	32
		650	94[h]	...	32
8	$\frac{1}{4}$-$\frac{5}{8}$ in.	1035	150	24	32
	>$\frac{5}{8}$-1 in.	1035	150	26	34
	>1-1$\frac{1}{2}$ in.	1035	150	26	36

(a) Determined on full-size nuts.

(b) Data from ASTM A 563M.

(c) For hex and hex-flange nuts only.

(d) Classes 853 and 1053 are not recognized in ISO standards. Classes 853 and 1053 have atmospheric corrosion resistance comparable to that of the steels covered in ASTM A 588 and A 242 (see the section "Corrosion Protection" in this article).

(e) Data from SAE J995.

(f) Normally applicable only to square nuts, which are normally available only in grade 2.

(g) For UNC, 9 UN thread series.

(h) For UNF, 12 UN threaded series and finer

Some of the ISO property class designations given in Tables 2 and 3 are used in various specifications, such as:

- SAE J1199, "Mechanical and Material Requirements for Metric Externally Threaded Steel Fasteners"
- ASTM F 568, "Specification for Carbon and Alloy Steel Externally Threaded Metric Fasteners"
- ASTM A 325M, "Specification for High-Strength Bolts for Structural Steel Joints (Metric)"
- ASTM A 490M, "Specification for High-Strength Steel Bolts, Classes 10.9 and 10.9.3, for Structural Steel Joints (Metric)"
- ASTM A 563M, "Carbon and Alloy Steel Nuts (Metric)"

However, not all of the ISO property classes are used in these specifications for metric steel threaded fasteners. Specification SAE J1199, for example, no longer allows the high-hardness fasteners (ISO bolt classes 12.8 and 12.9), because these two classes are susceptible to delayed brittle fracture in corrosive environments. This change in SAE J1199 is in response to the stress-corrosion cracking of class 12.8 bolts in automobile rear suspensions after just 2 years of service in the Snow Belt of the United States (Ref 1).

Strength grades for the U.S. system of mechanical fasteners with inch dimensions are often defined per SAE specifications. The SAE strength grades for bolts and nuts specified in inch dimensions are given in Tables 2 and 3. As can be seen in Tables 2 and 3, the SAE strength grade numbers do not directly convert to a specific strength level, although they are generally organized by strength level, that is, the greater the number, the higher the strength level. A second number, following a decimal point, is sometimes added to represent a variation of the product with the general strength level. However, this number after the decimal point does not represent a strength ratio, as in the ISO system.

In addition to the SAE specification of strength grades for steel threaded fasteners in the U.S. system, other strength grades can also be specified in ASTM standards. Table 1 shows the bolt markings for the SAE strength levels, along with a partial list of some ASTM bolt grades. When the bolt markings are the same, the SAE grade is equivalent to the ASTM grade. In selecting approximate equivalents between the ISO classes and the various grades specified by SAE and/or ASTM, the following equivalents are suggested (for guidance purposes only) in SAE J1199:

- ISO class 4.6 is approximately equivalent to SAE J429, grade 1, and ASTM A 307, grade A
- ISO class 5.8 is approximately equivalent to SAE J429, grade 2
- ISO class 8.8 is approximately equivalent to SAE J429, grade 5, and ASTM A 449
- ISO class 9.8 has properties approximately 9% stronger than SAE J429-grade 5, and ASTM A 449
- ISO class 10.9 is approximately equivalent to SAE J429-grade 8, and ASTM a 354-grade BD

Steels for Threaded Fasteners

Many different low-carbon, medium-carbon, and alloy steel grades are used to make all the various strength grades and property classes of threaded steel fasteners suitable for service between -50 and 200 °C (-65 and 400 °F). In addition to the effects of steel composition on corrosion resistance and elevated-temperature properties, the

hardenability of the steels used for threaded fasteners is important when selecting the chemical composition of the steel. As strength requirements and section size increase, hardenability becomes a major factor.

Grade 1022 steel is a popular low-carbon steel for threaded fasteners, although the low carbon content limits hardenability and therefore confines 1022 steel to the smaller diameter product sizes. For many product diameter sizes, grade 1038 steel is one of the most widely used steels for threaded fasteners up to the level of combined size and proof stress at which inadequate hardenability precludes further use. This medium-carbon steel has achieved its popularity because of excellent cold-heading properties, low cost, and availability.

Grade 1541 steel is extensively used for applications requiring hardenability greater than that of 1038 steel, but less than that of alloy steel. Figure 1 shows the depth of hardening when 19 mm ($\frac{3}{4}$ in.) diam bolts made of 1541 steel are oil quenched. Figure 1 also shows the depth of hardening with 1038 steel but with a water quench. (Figure 2 shows a more direct comparison of 1541 and 1038 hardenability.)

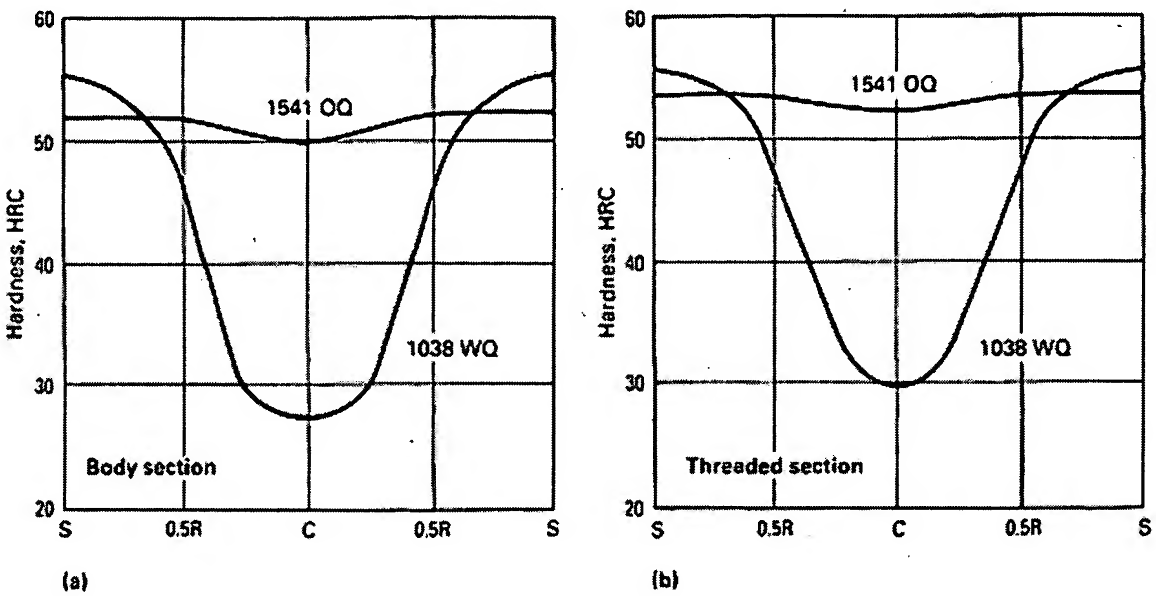
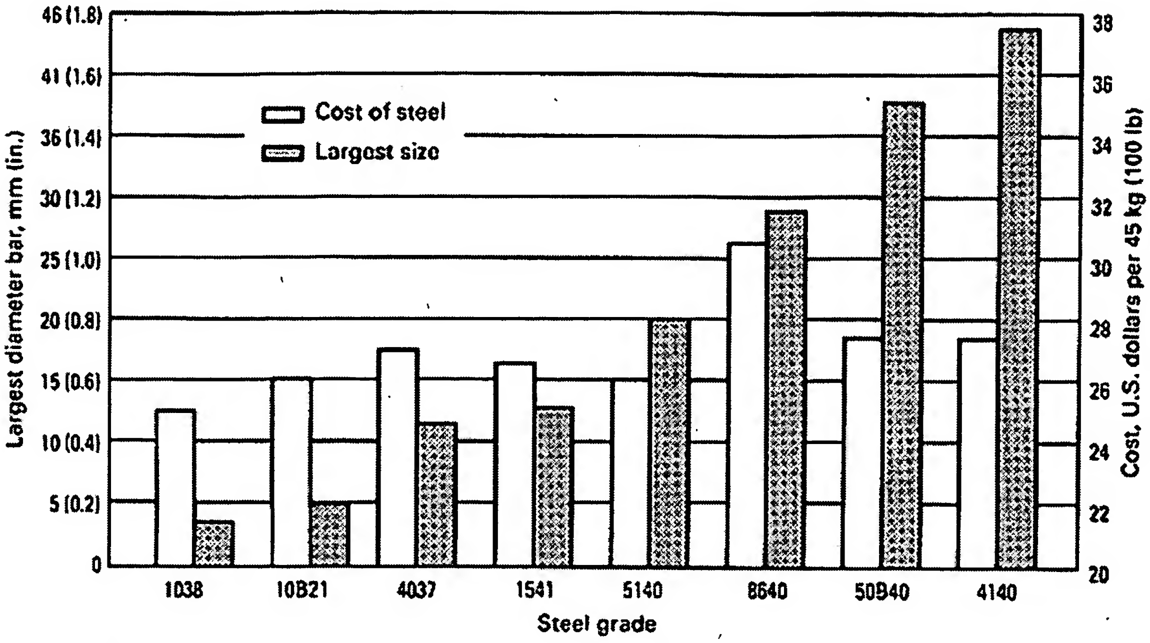
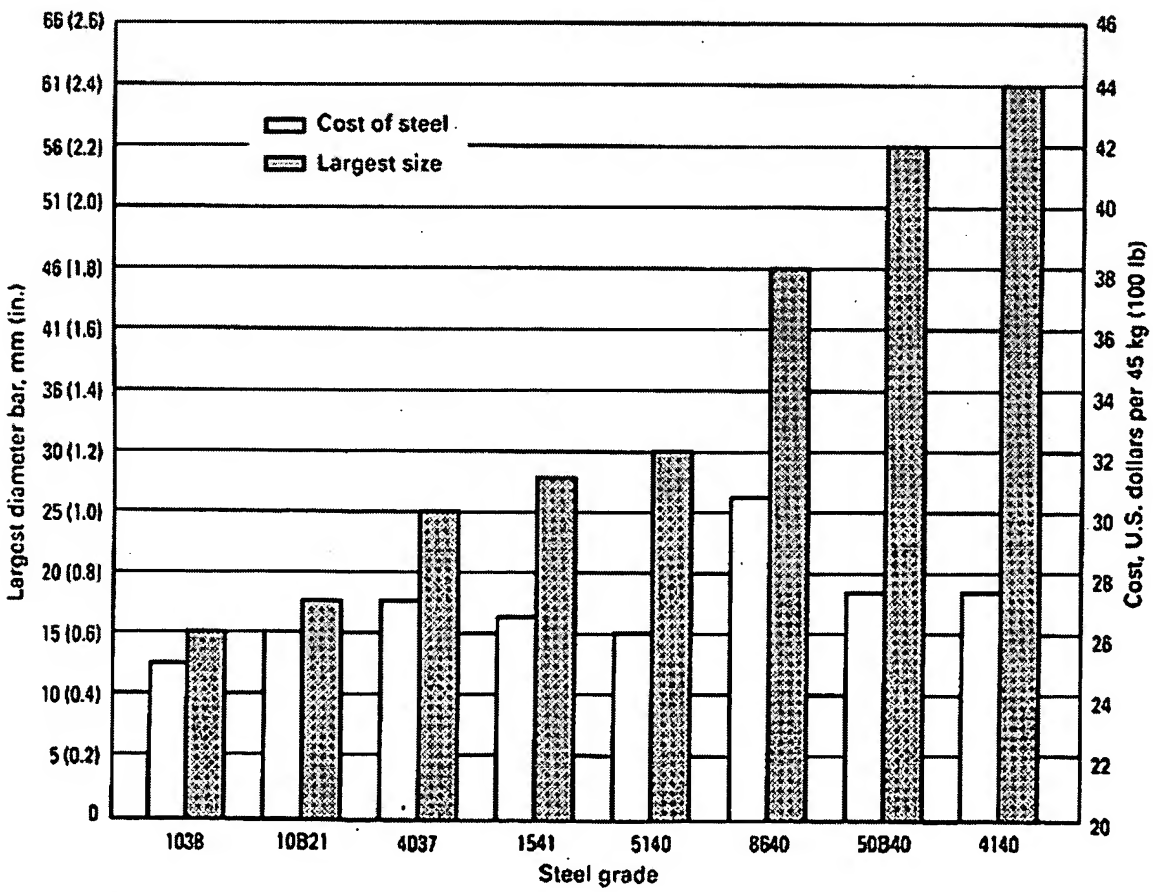


Fig. 1 Hardenability of 19 mm ($\frac{3}{4}$ in.) diam bolts made of 1541 steel and oil quenched. (a) Body section. (b) Threaded section. The curves represent the average as-quenched hardnesses of fifteen 19 mm ($\frac{3}{4}$ in.) diam bolts from one heat of each grade. C is center of the bolt, 0.5R is mid-radius, S is surface. The 1038 steel bolts were water quenched; the 1541 steel bolts, oil quenched.



Cost of steel
Largest size
Largest diameter bar, mm (in.)
46 (1.8)
41 (1.6)
36 (1.4)
30 (1.2)
25 (1.0)
20 (0.8)
15 (0.6)
10 (0.4)
5 (0.2)
0
Cost, U.S. dollars per 45 kg (100 lb)
38
36
34
32
30
28
26
24
22
20
1038
10B21
4037
1541
5140
8640
50B40
4140
Steel grade

(a)



Cost of steel
Largest size
Largest diameter bar, mm (in.)
66 (2.6)
61 (2.4)
56 (2.2)
51 (2.0)
46 (1.8)
41 (1.6)
36 (1.4)
30 (1.2)
25 (1.0)
20 (0.8)
15 (0.6)
10 (0.4)
5 (0.2)
0
Cost, U.S. dollars per 45 kg (100 lb)
46
44
42
40
38
36
34
32
30
28
26
24
22
20
1038
10B21
4037
1541
5140
8640
50B40
4140
Steel grade

(b)

Steel	Cost, U.S. dollars/ton[a]	Largest size to quench to 42 HRC in center			
		Oil		Water	
		mm	in.	mm	in.
1038	500	3.8	0.15	1.5	0.6
10B21	520	5	0.2	18	0.7
4037	540	11	0.45	25	1
1541	530	13	0.5	28	1.1
5140	520	20	0.8	36	1.4
8640	610	29	1.15	46	1.8
50B40	550	38	1.5	56	2.2
4140	550	44	1.75	61	2.4

(a) As of 1989

Fig. 2 Cost and hardenability relations for oil-quenched (a) and water-quenched (b) steels for cold-formed fasteners

Figure 2 shows cost-hardenability relationships for both oil- and water-quenched steels. An increase in hardenability does not necessarily mean an increase in cost per pound. Figure 2 is not intended to prescribe or imply the use of water quenching for alloy steels (which are normally oil quenched). These data are presented only to show the economic advantages of water quenching when it can be properly and successfully applied to the product being heat treated. Generally, the use of a water quench must be approached with caution, and a water quench practice is not necessarily recommended for some carbon steels (such as one of 1038 analysis) or requires careful analysis of part design, temperature control, and agitation to prevent quench cracking of low-carbon (SAE 1022) steel on an intermittent basis. Water quenching is precluded in most high-strength specifications due to uneven quenching and the resultant potential for quench cracking. For oil quenching, a large number of oil and synthetic quenchants are available. Synthetic quenchants must be monitored carefully because they can rapidly change in terms of quenching speed.

Bolt Steels. Table 4 lists the compositions for the bolt steel grades given in Table 2. As previously noted, the producer of bolts is free to use any steel within the grade and class limitations of Table 4 to attain the properties of the specified grade or class in Table 2. However, specific applications sometimes require special characteristics, and the purchaser will consequently specify the steel composition. However, except where a particular steel is absolutely necessary, this practice is losing favor. A specific steel may not be well-suited to the fastener producer's processing facilities; specification of such a steel may result in unnecessarily high cost to the purchaser.

Table 4 Chemical compositions of steel bolts and studs (including cap screws and U-bolts)

Strength grade or property class	Nominal diameter	Material and treatment	Composition, %[a]			
			C	P	S	Others
ISO property classes[b]						
4.6	5-100 mm	Low- or medium-carbon steel	0.55	0.048	0.058	. . .
4.8	1.6-16 mm	Low- or medium-carbon steel, partially or fully annealed as required	0.55	0.048	0.058	. . .
5.8	5-24 mm	Low- or medium-carbon steel, cold worked	0.13-0.55	0.048	0.058 [c]	. . .
8.8	16-72 mm	Medium-carbon steel, quenched and tempered[d][e]	0.25-0.55	0.048	0.058 [f]	. . .
	16-36 mm	Low-carbon martensite steel, quenched and tempered[g]	0.15-0.40	0.048	0.058	[h]
8.8.3	16-36 mm	Atmospheric corrosion resistant steel, quenched and tempered	See ASTM F 568.			[i]

9.8	1.6-16 mm	Medium-carbon steel, quenched and tempered	0.25-0.55	0.048	0.058 [f]	...
	1.6-16 mm	Low-carbon martensite steel, quenched and tempered[g]	0.15-0.40	0.048	0.058	[h]
10.9	5-20 mm	Medium-carbon steel, quenched and tempered[j][k]	0.25-0.55	0.048	0.058	...
	5-100 mm	Medium-carbon alloy steel, quenched and tempered[j]	0.20-0.55	0.040	0.045	...
	5-36 mm	Low-carbon martensite steel, quenched and tempered[j][g]	0.15-0.40	0.048	0.058	[h]
10.9.3	16-36 mm	Atmospheric corrosion resistant steel, quenched and tempered[j]	See ASTM F 568.			[i]
12.8[l][m]	1.6-20 mm	Low-carbon martensite boron steel, quenched and tempered[j][n]	0.16-0.27	0.038	0.048	[o]
12.9[m]	1.6-100 mm	Alloy steel, quenched and tempered[j]	0.31-0.65	0.045	0.045	[p]
SAE J429 strength grades						
1	$\frac{1}{4}$-1$\frac{1}{2}$ in.	Low- or medium-carbon steel	0.55	0.048	0.058	...
2	$\frac{1}{4}$-1$\frac{1}{2}$ in.	Low- or medium-carbon steel	0.55	0.048	0.058 [c]	...
4	$\frac{1}{4}$-1$\frac{1}{2}$ in.	Medium-carbon cold-drawn steel	0.55	0.048	0.13	...
5	$\frac{1}{4}$-1$\frac{1}{2}$ in.	Medium-carbon steel, quenched and tempered	0.28-0.55	0.048	0.058 [f]	...
5.1	$\frac{5}{8}$-$\frac{1}{2}$ in.	Low- or medium-carbon steel, quenched and tempered	0.15-0.30	0.048	0.058	...
5.2	$\frac{1}{4}$-1 in.	Low-carbon martensitic steel, fully killed, fine grain, quenched and tempered	0.15-0.25	0.048	0.058	[h]
7	$\frac{1}{4}$-1$\frac{1}{4}$ in.	Medium-carbon alloy steel, quenched and tempered[q][r]	0.28-0.55	0.040	0.045	...
8	$\frac{1}{4}$-1$\frac{1}{4}$ in.	Medium-carbon alloy steel, quenched and tempered[q][r]	0.28-0.55	0.040	0.045	...
8.1	$\frac{1}{4}$-1$\frac{1}{4}$ in.	Drawn steel for elevated-temperature service: medium-carbon alloy steel or 1541 steel	0.28-0.55	0.048	0.058	...
8.2	$\frac{1}{4}$-1 in.	Low-carbon martensitic steel, fully killed, fine grain, quenched and tempered[s]	0.15-0.25	0.048	0.058	[h]

(a) All values are for product analysis; where a single value is shown, it is a maximum.

(b) Data from ASTM F 568.

(c) For studs only, sulfur content may be 0.33% max.

(d) For diameters through 24 mm, unless otherwise specified by the customer, the producer can use a low-carbon martensitic steel with 0.15-0.40% C, 0.74% Mn (min), 0.048% P (max), 0.058% S (max), and 0.0005% B (min.).

(e) At producer's option, medium-carbon alloy steel can be used for diameters over 24 mm.

(f) For studs only, sulfur content may be 0.13% max.

(g) Requires special marking; see ASTM F 568.

(h) 0.74% Mn (min) and 0.0005% B (min).

(i) Available in six different types of compositions that include carbon, manganese, phosphorus, sulfur, silicon, copper, nickel, chromium, and vanadium or molybdenum in a few types. Selection of a type is at the option of the producer.

(j) Steel for classes 10.9, 10.9.3, 12.8, and 12.9 products shall be fine grain and have a hardenability that will achieve a structure of approximately 90% martensite at the center of a transverse section one diameter from the threaded end of the product after oil quenching.

(k) Carbon steel can be used at the option of the manufacturer for products of nominal thread diameters 12 mm and smaller.

When approved by the purchaser, carbon steel can be used for products of diameters larger than 12 mm through 20 mm, inclusive.

(l) No longer specified in SAE J1199.

(m) Data obtained from the old (prior to Sept 1983) version of SAE J1199 and provided for information only.

(n) Class 12.8 bolts required heat treatment in a continuous-type furnace having a protective atmosphere, and under no circumstances should heat treatment or carbon restoration be accomplished in the presence of nitrogen compounds, such as carbonitriding or cyaniding.

(o) 0.74-1.46% Mn and 0.0005-0.003% B.

(p) One or more of the alloying elements chromium, nickel, molybdenum, or vanadium shall be present in sufficient quantity to ensure that the specified strength properties are met after quenching and tempering.

(q) Fine-grain steel with hardenability that will produce 47 HRC min at the center of a transverse section one diameter from the threaded end of the fastener after oil quenching (see SAE J407).

(r) For diameters of $\frac{1}{4}$ through $\frac{3}{4}$ in., carbon steel can be used by agreement. At producer's option, 1541 steel, oil quenched and tempered, can be used for diameters through $\frac{7}{16}$ in.

(s) Steel with hardenability that will produce 38 HRC min at the center of a transverse section one diameter from the threaded end of the fastener after quenching

Most bolts are made by cold or hot heading. Resulfurized steels are used in the manufacture of nuts, but because of their tendency to split, these grades are not routinely used in the production of headed bolts. A more recent development relates to the use of calcium-treated steels instead of the C-1100 series steels for headed-bolt manufacture. Documented machinability data remain somewhat limited, but there are indications that the calcium-treated steels not only head well but also offer definite machinability benefits. Only a few bolts are machined from bars; these are usually of special design or the required quantities are extremely small. For such bolts, the extra cost for resulfurized grades of steel may be justified. For example, 1541 steel might be selected to make headed bolts of a specific size. If the same bolts were to be machined from bars, 1141 steel would be selected because of its superior machinability. Special bolts can usually be made more economically by machining from oversize upset blanks instead of from bars.

Stud Steels. The chemical compositions of studs (and U-bolts, which are basically studs formed into a U-shape) are given in Table 4; special modifications that apply to studs can be found in the footnotes. Because studs (and U-bolts) are not headed, it is not essential to restrict sulfur. It may be noted that grade 2 and class 5.8 permit 0.33% maximum sulfur, while grade 5 and classes 8.8 and 9.8 permit 0.13% maximum sulfur.

Stud (or U-bolt) threads, however, are not necessarily cut, but can be rolled for economy and good thread shape. A smaller-diameter rod must be used to roll a specific thread size than to cut the same thread size from rod. For example, a $\frac{1}{2}$-13 thread could be cut from a rod 12.7 mm (0.500 in.) in diameter; a smaller diameter rod would be used to roll the same size threads. Grades 4 and 8.1 are made from a medium-carbon steel and obtain their mechanical properties not from quenching and tempering but from being drawn through a die with special processes. They are particularly suitable for studs because these materials cannot readily be formed into bolts.

Selection of Steel for Bolts and Studs. The following guidelines should be considered when selecting steel for bolts and studs (including cap screws and U-bolts):

- Depending on the capabilities of a facility, bolts up to 305 mm (12 in.) in length and 32 mm ($1\frac{1}{4}$ in.) in diameter can be cold headed. For shops not having this or similar specialized equipment, bolts more than 150 mm (6 in.) in length or more than 19 mm ($\frac{3}{4}$ in.) in diameter may have to be hot headed
- Strength requirements for steels for grade 1 bolts can be met with hot-rolled low-carbon steels
- Depending on the manufacturing method, the strength requirements for steels for grade 2 bolts ranging from 19 to 32 mm ($\frac{3}{4}$ to $1\frac{1}{4}$ in.) or less in diameter can be met with cold-drawn low-

carbon steels; sizes larger than this diameter range of 19 to 32 mm ($\frac{3}{4}$ to $1\frac{1}{4}$ in.) require hot-rolled low-carbon steel only if the bolt is hot headed, but may be made of cold-finished material

- Grade 4 fasteners (studs only) require a cold-finished medium-carbon steel, specially processed to obtain higher-than-normal strength. Resulfurized steels are acceptable
- Grade 5 bolts and studs require quenched and tempered steel. The choice among carbon, 1541, and alloy steel will vary with the hardenability of the material, the size of the fastener, and the quench employed. Cost favors the use of carbon steel, including 1541; however, the possibility of quench cracking and excessive distortion determines the severity of the quench that can be used. The threading practice (before or after hardening) also determines the severity of quench that can be used if quench cracks in the threads are to be avoided. Generally, the use of a water quench must be approached with caution
- Fasteners made to grade 7 and 8 specifications normally require medium-carbon, fine-grain alloy steel. This steel is selected on a hardenability basis so a minimum of 90% martensite exists at the center after oil quenching. SAE J429 requires oil quenching of these two grades
- Fasteners of SAE grades 5.2 and 8.2 are made from low-carbon martensitic boron steels. These steels (and the low-carbon versions of ISO classes 8.8, 9.8, and 10.9 in Table 4) are readily formed because of the low carbon content, yet the boron gives them relatively high hardenability. Fasteners of these grades are hardened in oil or water, then tempered at minimum temperatures of 425 °C (800 °F) for the 8.2 grade and 340 °C (650 °F) for the 5.2 grade. Grades 5.2 and 8.2 are expected to offer the same mechanical properties as the corresponding nonboron grades 5 and 8 (Fig. 3), but grades 5.2 and 8.2 may have slightly better toughness and ductility than the medium-carbon 5 and 8 grades at comparable hardness levels. *Caution: Grades 5.2 and 8.2 should be used with caution due to the potential for tempering (softening) at lower temperatures than grade 5 or 8 fasteners*
- ISO bolt class 12.8 is also made from a low-carbon martensitic (boron) steel. *Caution: However, this class of bolt is susceptible to stress-corrosion cracking and should be used with caution. This bolt class is no longer specified in SAE J1199 because of failures in automobiles after just two years of service (Ref 1).*
- *Caution: ISO bolt class 12.9 has also been removed from SAE J1199. Caution is advised when considering the use of class 12.9 bolts and screws because, like the 12.8 class, the 12.9 class is susceptible to stress-corrosion cracking.* The capability of the bolt manufacturer, as well as the anticipated in-use environment, should be considered for both the 12.8 and 12.9 classes. High-strength products such as class 12.9 require rigid control of the heat-treating operations and careful monitoring of as-quenched hardness, surface discontinuities, depth of partial decarburization, and freedom from carburization. Some environments may cause stress-corrosion cracking of nonplated as well as electroplated products
- For service temperatures of 200 to 370 °C (400 to 700 °F), specific bolt steels are recommended (Table 5) because relaxation is an influencing factor at these temperatures. Although other steels will fulfill requirements for the tabulated conditions, those listed are the commonly used grades. Only medium-carbon alloy steels are recommended; in all instances, they should be quenched and tempered

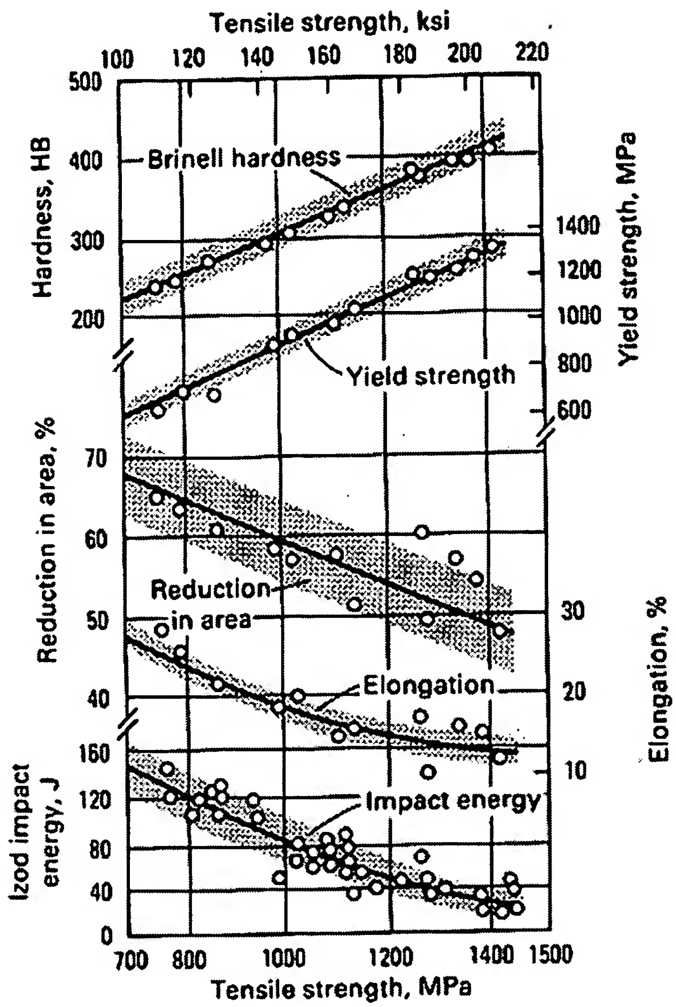


Fig. 3 Tensile and impact properties of fully quenched and tempered boron steels superimposed on normal expectancy bands for medium-carbon low-alloy steels without boron

Table 5 Recommended steels for bolts to be used at temperatures between 200 and 370 °C (400 and 700 °F)

All selections are based on a minimum tempering temperature of 455 °C (850 °F).

Bolt diameter		Steel recommended for a proof stress (at room temperature) of:		
mm	in.	520 MPa (75 ksi)	690 MPa (100 ksi)	860 MPa (125 ksi)
6.3-19	$\frac{1}{4}$-$\frac{3}{4}$	1038	4037	4037
19-32	$\frac{3}{4}$-1 $\frac{1}{4}$	1038	4140	4140
32-50	1 $\frac{1}{4}$-2	4140	4140	4145

Nut Steels. The selection of steel for nuts is less critical than for bolts. The nut is usually not made from the same material as the bolt. Table 6 gives the chemical composition requirements for each property grade and class of steel nut shown in Table 3.

Table 6 Chemical compositions of steel nuts

	Composition, %[a]

Strength grade or property class	C (max)	Mn (min)	P (max)	S (max)
SAE strength grades[b]				
2	0.47	. . .	0.12[c]	0.15[d]
5	0.55	0.30	0.05[e][f]	0.15[d][f]
8	0.55	0.30	0.04	0.05[g]
ISO property classes[h]				
5[i] and 9	0.55	. . .	0.04	0.15[c][d]
8S	0.55	. . .	0.04	0.15
10	0.55	0.30	0.04	0.05[j]
853[k]	See ASTM A 563M.			
1053[k]	See ASTM A 563M.			
12	0.20-0.55	0.60	0.04	0.05[j]

(a) All values for heat analysis.

(b) Data from SAE J995.

(c) Resulfurized and rephosphorized material is not subject to rejection based on check analysis for sulfur.

(d) If agreed, sulfur can be 0.23% max.

(e) For acid bessemer steel, phosphorus can be 0.13% max.

(f) If agreed, phosphorus can be 0.12% max and sulfur can be 0.35% max, provided manganese is 0.70% min.

(g) If agreed, sulfur can be 0.33% max, provided manganese is 1.35% min.

(h) Data from ASTM A 563M.

(i) If agreed, free-cutting steel having maximums of 0.34% S, 0.12% P, and 0.35% Pb can be used.

(j) If agreed, sulfur can be 0.15% max with a minimum of 1.35% Mn.

(k) Corrosion-resistant grades are not included in ISO classifications. Class 853 is used with bolt grade 8.8.3 and has a selection of steel compositions at the option of the manufacturer. Class 1053 is used with bolt grade 10.9.3.

Lower-strength nuts (such as grades 2 and 5) are not heat treated. However, higher-grade nuts (such as grade 8) can be heat treated to attain specified hardness.

Nuts are machined from bar stock, cold formed or hot formed, depending on configuration and production requirements. Size and configuration are usually more important than the material from which the nuts are made.

The bolt is normally intended to break before the nut threads strip. Regular hex nut dimensions are such that the shear area of the threads is greater than the tensile stress area of the bolt by more than 100%. Consequently, low-carbon steel nuts are customarily used even when the bolts are made of much higher strength material.

Low-carbon steel nuts are usually heat treated to provide mar resistance to the corners of the head or to the clamping face. Light case carburizing or carbonitriding is often employed to improve mar resistance.

When nuts are to be quenched and tempered, the steel must have the appropriate hardenability. Increasing the amounts of carbon and manganese or adding other alloying elements to provide increased hardenability will decrease the suitability of the material for cold forming. For this reason, low-carbon boron steels are widely used for quenched and tempered high-strength nuts. The low carbon content permits easy cold forming, while the boron enhances hardenability. Threading can be done before or after heat treatment, depending on the class of thread fit required and the hardness of the heat-treated nut.

Because the selection of steel for nuts is not critical, practice varies considerably. A common practice is to use steels such as 1108, 1109, 1110, 1113, or 1115, cold formed or machined from cold-drawn bars, for grade 2 nuts. Grade 5 nuts are commonly made from 1035 or 1038 steels, cold formed from annealed bars, cold drawn and stress relieved, or quenched and tempered. Grade 8 nuts are formed from low-carbon boron steels, then quenched and tempered.

Corrosion Protection

The most commonly used protective metal coatings for ferrous metal fasteners are zinc, cadmium, and aluminum. Tin, lead, copper, nickel, and chromium are also used, but only to a minor extent and for very special applications. In many cases, however, fasteners are protected by some means other than metallic coatings. They are sometimes sheltered from moisture or covered with a material that prevents moisture from making contact, thus drastically reducing or eliminating corrosion. For fasteners exposed to the elements, painting is universally used.

The low-alloy high-strength steel conforming to ASTM A 242 and A 588 forms its own protective oxide surface film. This type of steel, although it initially corrodes at the same rate as plain carbon steel, soon exhibits a decreasing corrosion rate, and after a few years, continuation of corrosion is practically nonexistent. The oxide coating formed is fine textured, tightly adherent, and a barrier to moisture and oxygen, effectively preventing further corrosion. Plain carbon steel, on the other hand, forms a coarse-textured flaky oxide that does not prevent moisture or oxygen from reaching the underlying noncorroded steel base.

The 853 and 1053 class nuts (Table 3) and bolt classes 8.8.3 and 10.9.3 (Table 4) have corrosion resistance characteristics similar to those of steels conforming to ASTM A 242 and A 588. These weathering steels are suitable for resisting atmospheric corrosion and have an atmospheric corrosion resistance approximately two times that of carbon structural steel with copper. However, these weathering steels are not recommended for exposure to highly concentrated industrial fumes or severe marine conditions, nor are they recommended for applications in which they will be buried or submerged. In these environments, the highly protective oxide does not form properly, and corrosion is similar to that for plain carbon steel.

Zinc Coating. Zinc is the coating material most widely used for protecting fasteners from corrosion. Electroplating and zinc phosphating are the two most frequently used method of application, followed by hot dipping and, to a minor extent, mechanical plating.

Hot dipping, as the name implies, involves immersing parts in a molten bath of zinc. Hot dip zinc coatings are sacrificial by electrochemical means, and these coatings for fasteners are covered in ASTM A 394. Zinc electroplating of fasteners is done primarily for appearance, where thread fit is critical, where corrosion is not expected to be severe, or where life expectancy is not great.

Specification ASTM B 633 for electrodeposited zinc coatings on steel specifies three coating thicknesses: GS, 25 μm (0.0010 in.); LS, 13 μm (0.0005 in.); and RS, 4 μm (0.00015 in.). These electrodeposited coatings are often given supplemental chromate coatings to develop a specific color and to enhance corrosion resistance. The corrosion life of a zinc coating is proportional to the amount of zinc present and chromate finish; therefore, the heaviest electrodeposited coating (GS) would have only about half the life of a hot dip galvanized coating.

Mechanical (nonelectrolytic) barrel plating is another method of coating fasteners with zinc. Coating weight can be changed by varying the amount of zinc used and the duration of barrel rotation. Such coatings are quite uniform and have a satisfactory appearance.

Cadmium coatings are also applied to fasteners by an electroplating process similar to that used for zinc. These coatings are covered in ASTM A 165. As is true for zinc, cadmium corrosion life is proportional to the coating thickness. The main advantage of cadmium over zinc is its much greater resistance to corrosion in marine environments and uniformity of torque-tension relationship. Cadmium-plated steel fasteners are also used in aircraft in contact with aluminum because the galvanic characteristics of cadmium are more favorable than those of zinc. Chromate coatings are also used over cadmium coatings for the reasons given for zinc-plated fasteners.

Aluminum coating on fasteners offers the best protection of all coatings against atmospheric corrosion.

Aluminum coating also gives excellent corrosion protection in seawater immersion and in high-temperature applications.

Aluminum coatings are applied by hot dip methods at about 675 to 705 °C (1250 to 1300 °F). Aluminum alloy 1100 is usually used because of its general all-around corrosion resistance. As with any hot dip coating, a metallurgical bond is formed that consists of an intermetallic alloy layer overlaid with a coating of pure bath material.

Aluminum coatings do not corrode uniformly, as do zinc and cadmium coatings, but rather by pitting. In some cases, these pits may extend entirely through the coating to the base metal; in others, only through the overlay to the intermetallic layer. Pits, which may occur in a part soon after exposure, sometimes discolor the coated surface but cause little damage. The complex aluminum and iron oxide corrosion product seals the pits, and because the corrosion product is tightly adherent and impervious to attack, corrosion is usually limited. There is little tendency for corrosion to continue into the ferrous base, and there is none for undercutting and spalling of the coating.

Aluminum coatings will protect steel from scaling at temperatures up to about 540 °C (1000 °F); the aluminum coating remains substantially the same as when applied, and its life is exceptionally long. Above 650 °C (1200 °F), the aluminum coating diffuses into the steel to form a highly protective aluminum-iron alloy. This diffusing or alloying is time-temperature dependent; the higher the temperature, the faster the diffusion. However, scaling will not take place until all the aluminum is used up, which may take a thousand or more hours even at temperatures as high as 760 °C (1400 °F).

The prevention of galling at elevated temperatures is another characteristic of aluminum coatings. Stainless steel fasteners for use at 650 °C (1200 °F) have been aluminum coated just to prevent galling. Coated nuts can be removed with an ordinary wrench after many hours at these temperatures, which is impossible with uncoated nuts.

Fastener Performance at Elevated Temperatures

Selection of fastener material is perhaps the single most important consideration in elevated-temperature design. The basic design objective is to select a bolt material that will give the desired clamping force at all critical points in the joint.

Time- and Temperature-Related Factors. To achieve the basic design objective mentioned above, it is necessary to balance the three time- and temperature-related factors (modulus, thermal expansion, and relaxation) with a fourth factor--the amount of initial tightening or clamping force. These three time- and temperature-related factors affect the elevated-temperature performance of fasteners as follows.

Modulus of Elasticity. As temperature increases, the modulus of elasticity decreases; therefore, less load (or stress) is needed to impact a given amount of elongation (or strain) to a material than at lower temperatures. This means that a fastener stretched a certain amount at room temperature to develop preload will exert a lower clamping force at higher temperature.

Coefficient of Expansion. With most materials, the size of the part increases as the temperature increases. In a joint, both the structure and the fastener increases in size with an increase in temperature. If the coefficient of expansion of the fastener exceeds that of the joined material, a predictable amount of clamping force will be lost as temperature increases. Conversely, if the coefficient of expansion of the joined material is greater, the bolt may be stressed beyond its yield or even fracture strength, or cyclic thermal stressing may lead to thermal fatigue failure. Thus, matching of materials in joint design can ensure sufficient clamping force at both room and elevated temperatures without overstressing the fastener.

Relaxation. In a loaded bolt joint at elevated temperature, the bolt material will undergo permanent plastic deformation (creep) in the direction of the applied stress. This phenomenon, known as relaxation in loaded-joint applications, reduces the clamping force with time. Relaxation is the most important of the three time- and temperature-related factors and is discussed in more detail in the article "Elevated-Temperature Properties of Ferritic Steels" in this Volume.

Bolt Steels for Elevated Temperatures. Table 5 lists the recommended steels for bolts to be used at temperatures between 200 and 370 °C (400 and 700 °F). For higher temperatures up to 480 °C (900 °F), other alloy steels are used. For example, the medium-alloy chromium-molybdenum-vanadium steel conforming to ASTM A 193, grade B 16, is a commonly used bolt material in industrial turbine and engine applications to 480 °C (900 °F). An aircraft version of this steel, AMS 6304, is widely used in fasteners for jet engines. The 5% Cr tool steels, most notably H11, are also used for fasteners having a tensile strength of 1500 to 1800 MPa (220 to 260 ksi). They retain excellent strength through 480 °C (900 °F).

For temperatures above 480 °C (900 °F), heat-resistant alloys or superalloys are used for bolt materials. From 480 to 650 °C (900 to 1200 °F), corrosion-resistant alloy A-286 is used. Alloy 718, with a room-temperature tensile strength of 1240 MPa (180 ksi), has some applications in this temperature range. The nickel-base alloys René 41, Waspaloy, and alloy 718 can be used for most applications in the temperature range of 650 to 870 °C (1200 to 1600 °F).

Coatings for Elevated Temperatures. At moderate temperatures, where cadmium and zinc anticorrosion platings might normally be used, the phenomenon of stress alloying becomes an important consideration. Conventional cadmium plating, for example, is usable only to 230 °C (450 °F). At somewhat above that temperature, the cadmium is likely to melt and diffuse into the base material along the grain boundaries, causing cracking by liquid-metal embrittlement, which can lead to rapid failure. For corrosion protection of high-strength alloy steel fasteners used at temperatures between 230 and 480 °C (450 and 900 °F), special nickel-cadmium coatings such as that described in AMS 2416 are often used. At extremely high temperatures, coatings must be applied to prevent oxidation of the base material.

Effect of Thread Design on Relaxation. Fastener-manufacturing methods can also influence bolt performance at elevated temperature. The actual design and shape of the threaded fastener are also important, particularly the root of the thread. A radiused thread root is a major consideration in room-temperature design, being a requisite for good fatigue performance. However, at elevated temperature, a generously radiused thread root is also beneficial in relaxation performance. Starting at an initial preload of 483 MPa (70 ksi), a Waspaloy stud with square thread roots lost a full 50% of its clamping force after 20 h, with the curve continuing downward, indicating a further loss. A similar stud made with a large-radiused root lost only 36% of preload after 35 h.

Reference cited in this section

1. T.J. Hughel, "Delayed Fracture of Class 12.8 Bolts in Automotive Rear Suspensions," SAE Technical Paper Series 820122, Society of Automotive Engineers, 1982

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